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Reliability optimization of binary state non-repairable systems: A state of the art survey

Roya Soltani*

School of Industrial Engineering, Iran University of Science and Technology, Tehran, Iran

C H R O N I C L E

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A B S T R A C T

The purpose of this paper is to discuss the state of the art on models and methods for reliability optimization problems (ROPs) including reliability allocation, redundancy allocation and reliability-redundancy allocation. There are literally few surveys for reviewing the literature of the ROPs. Tillman et al. (1980) classified the related papers by system structure, problem type, and solution methods, separately. In another work, Tzafestas (1980) reviewed system reliability optimization models and the optimization techniques. Yearout (1986) reviewed the literature related to standby redundancy. Kuo (2000) studied the system reliability optimization based on system structure and solution methods. Kuo and Prasad (2004) overviewed system reliability optimization methods. Later, Kuo (2007) reviewed recent advances in optimal reliability allocation problems. The present study adds to the previous literature surveys and focuses mainly on papers after year 2000 but with a quick review on the previous works so that the readers become familiar with the existing approaches. This research investigates the literature from system structure, system performance, uncertainty state and solution approach standpoints, simultaneously.

Acronyms

ROP: Reliability Optimization Problem
RAP: Redundancy Allocation Problem
RRAP: Reliability- Redundancy Allocation Problem
GA: Generic Algorithm
SA: Simulated Annealing
GP: Geometric Programming
HBMO: Honey Bee Mating Optimization
ABC: Artificial Bee Colony
ACO: Ant Colony Optimization
DC: Degrade Ceiling
PSO: Particle Swarm Optimization
IA: Immune Algorithm
DE: Differential Evolution
HS: Harmony Search
VND: Variable Neighborhood Descent
VNS: Variable Neighborhood Search
EGHS: Effective Global Harmony Search
NGHS: Novel Global Harmony Search
SOMA: Self-Organizing Migrating Algorithm
BBMOPSO: Bare- Bones Multi-Objective Particle Swarm Optimization
DSAMOPSO: Dynamic Self-Adaptive Multi-Objective Particle Swarm Optimization
AUGMECON: Augmented Epsilon Constraint
CTV-MOPSO: Customized Time-Variant Multi- Objective Particle Swarm Optimization
UMOSA: Ulungu Multi-Objective Simulated Annealing
LMBB: Lagrange Multiplier and the Branch-and-Bound
ICA: Imperialist Competitive Algorithm
FLC: Fuzzy Logic Controller
TS: Tabu Search
IIMOM: Intelligent Interactive Multi-Objective Optimization Method
GDA: Great Deluge Algorithm
CEA: Cellular Evolutionary Approach
NSGA-II: Non-dominated Sorting Genetic Algorithm
EVM : Expected Value Model
CCP : Chance-Constrained Programming (Redundancy CCP)
DCP: Dependent Chance Programming
MC: Monte Carlo
MCS: Monte Carlo Simulation
RSM: Response Surface Methodology
BBD: Box-Behnken design
OSSO: Orthogonal Simplified Swarm Optimization
SPEA2: Strength Pareto Evolutionary Genetic Algorithm
MOHGA: Multi-objective hierarchical genetic algorithm
SMOSA: Suppapitnarm Multi-Objective Simulated Annealing
PSA: Pareto Simulated Annealing
PDMOSA: Pareto Domination based Multi-Objective Simulated Annealing
WMOSA: Weight based Multi-Objective Simulated Annealing
LHS: Latin Hypercube Sampling
NN: Neural Network

* Corresponding author.
E-mail: royasoltani@iust.ac.ir (R.Soltani)

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1. Introduction

To be more competitive in the market, the reliabilities of systems or products need to be optimized by system designers. This goal is accomplished by applying suitable reliability optimization techniques, which includes three main categories, i.e. the reliability allocation, the redundancy allocation and the reliability-redundancy allocation as presented in Fig. 1. Redundancy can be in system level, subsystem level (Module) and component level.

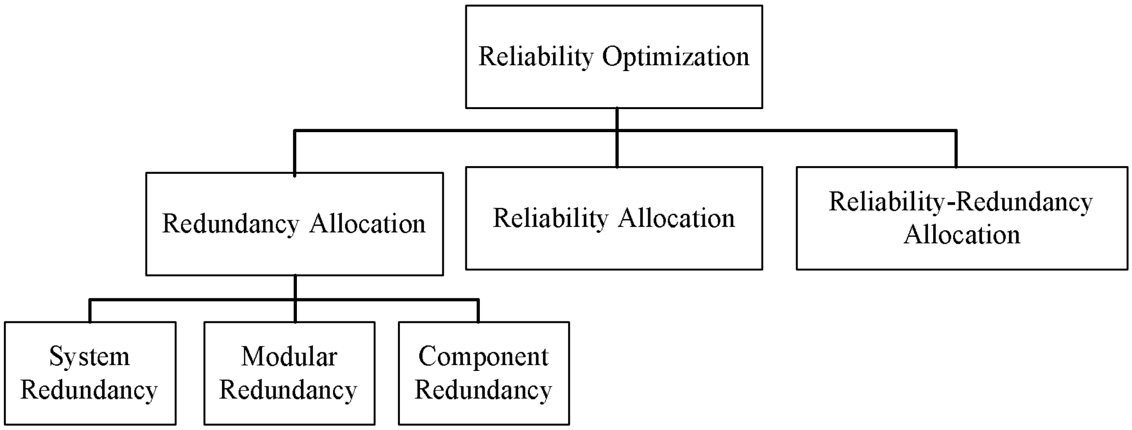

Fig. 1. Reliability optimization problems

In the reliability allocation problems, the reliability levels of the components is determined such that the consumption of a resource under a reliability constraint is minimized while the redundancy allocation problem generally involves the selection of components and redundancy levels to maximize the system reliability given various system-level's constraints. The reliability-redundancy allocation, which is the combination of two aforesaid problems, determines the reliability levels and the redundancy levels, simultaneously.

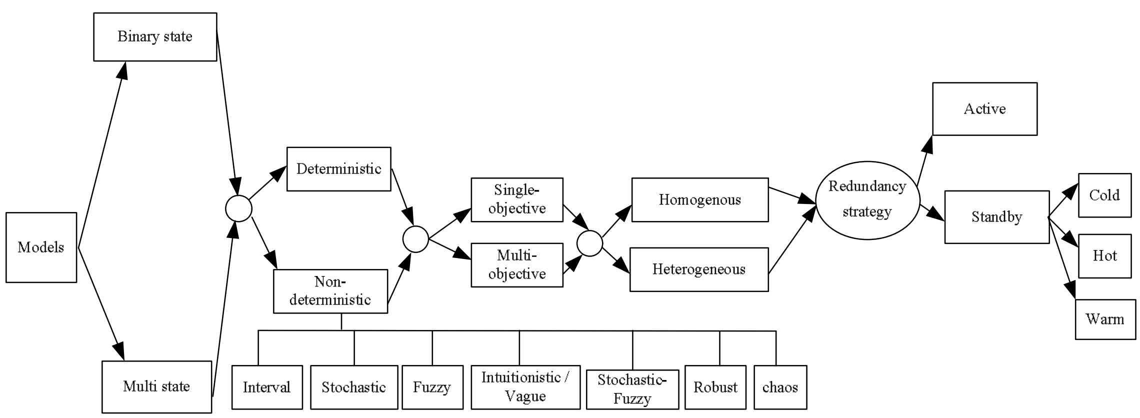

Fig. 2. RAP models

Fig. 2 presents taxonomy of redundancy allocation problems. By starting from the model and going through each path, a new model is resulted. The RAP is first classified and separated based on whether the problem is binary state or multi state. In the former, the components are in two states of functioning and non-functioning whilst in the latter, the states between them are also considered. Each of these categories can be studied with deterministic or non-deterministic parameters, which involve uncertainties such as stochastic uncertainty, interval uncertainty, fuzzy uncertainty, intuitionistic fuzzy or vague set, stochastic-fuzzy uncertainty, perturbation in a defined uncertainty set and chaos. Each problem can be modelled with a single objective or multiple objectives each of which with homogenous and heterogeneous components. The redundancy strategy can be either active or standby. The standby redundancy in turn is categorized into cold, hot and warm. The models have been formulated with different system structures and with different performance measures such as reliability, availability, mean time to failure (average life), percentile life, etc. For more information about the application of percentile life and reliability as performance measures readers are referred to the work by Kim and Kuo (2003). Note that fault-tolerance mechanisms, which are the ability of a system to continue performing its intended function in spite of faults, are not investigated in this research.

Fig. 3 classifies the solution methods for RAPs. Mathematical programming methods, which include exact and approximation methods are the most suitable for small-sized problems. Chern (1992) proves that RAP in series system is an NP-Hard problem. As the system configuration becomes complex and other simplified assumptions are released the NP-Hardness of the problem increases. Therefore, heuristic and meta-heuristic approaches have been proposed to deal with RAPs.

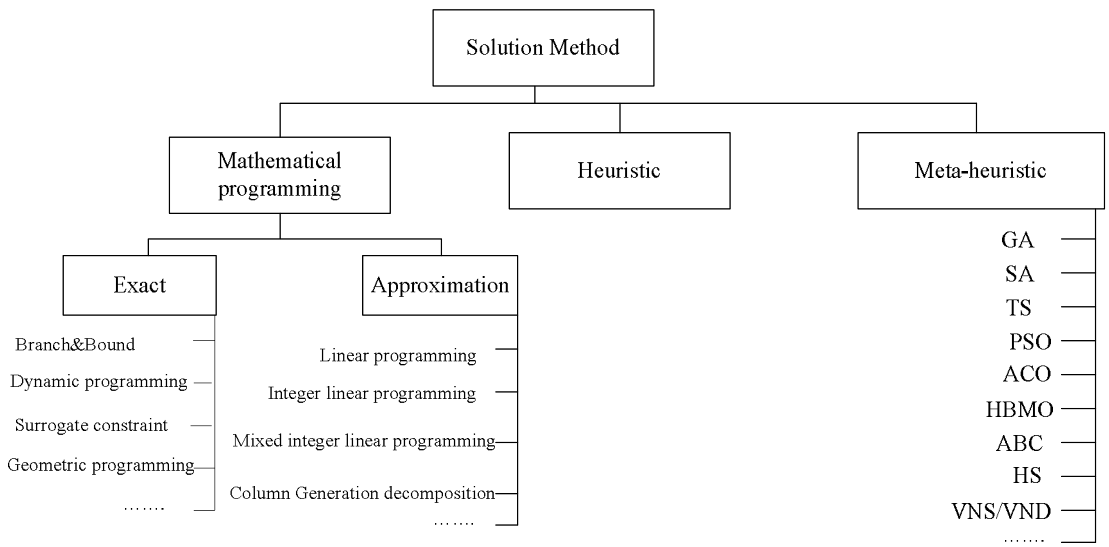

Fig. 3. RAP solution methods

The rest of the paper is organized as follows. In section 2 the RAP is investigated which include deterministic and non-deterministic models. Section 3 is devoted to reliability allocation. Section 3 surveys the reliability-redundancy allocation problems. Finally, concluding remarks have been provided in section 4.

2. Redundancy allocation

As presented in Fig.1, redundancy can be in system level (i.e. system redundancy), in subsystem level (i.e. modular redundancy) or in component level (i.e. component redundancy). It is a well-known principle to the design engineers that active redundancy at the component level is better than that at the system level in usual stochastic ordering (Nanda & Hazra, 2013; Barlow & Proschan, 1975). In the following subsections, modular and component redundancies are investigated regarding deterministic or non-deterministic parameters. Redundancy can be in active or standby forms. Yearout et al. (1986) and Li and Ding (2013) respectively reviewed standby and active redundancies in reliability.

Basic assumptions for RAP are as follows:

1) The availability of the components is unlimited;

2) Failures of individual components are independent;

3) All failed components will not damage the system and are not repaired.

4) No preventive maintenance is considered.

In the followings, other assumptions such as redundancy strategy, being deterministic or non-deterministic, etc. are mentioned. Furthermore, wherever a basic assumption is violated, it is mentioned in a column named other considerations.

2.1 Component redundancy

2.1.1 Deterministic models

Deterministic models assume that all parameters including component reliability, cost, weight, volume, etc. are known, precisely. The RAP is restricted by available system cost, weight, volume, etc. In the field of system-reliability, it has been reported that various exact/mathematical programming and heuristic/meta-heuristic techniques have been used to cope with RAPs. For review on the work before year 2000 readers are referred to the works by Tillman et al. (1980), Kuo (2000), Kuo and Prasad (2004) and Kuo (2007). In the area of single objective models with active strategy, Fyffe et al. (1968) were the first who proposed a model for RAP where system's reliability is maximized subject to constraints on cost and weight. They used a Lagrangian multiplier in the objective function to handle multiple constraints.

Nakagawa and Miyazaki (1981) showed that, sometimes, the use of a Lagrangian multiplier becomes inefficient. Therefore, they proposed the *surrogate constraint* approach. Other exact and mathematical programming techniques include *DP* (e.g. Bellman & Dreyfus, 1958; Fyffe et al., 1968; Jianping, 1996; Misra, 1971), Integer programming (e.g. Ghare, 1969; Misra & Sharma, 1991), Partial bound enumeration (e.g. Jianping & Xishen , 1997), Branch and bound (e.g. Bulfin & Liu,1985; Sup & Kwon,1999), GP (e.g. Federowicz & Mazumdar,*1968;* Govil, 1983*;* Misra & Sharma*,* 1973), Lagrange Multiplier (Govil & Agarwala,1983), etc.

Table 1 lists the related works in the literature after year 2000. Note that the references are not arranged in chronological order but they are arranged based on the solution method. As it is observed, most works have been carried out in active redundancy area except the work by Amari (2010) and Tannous et al. (2011) which consider both active and/or warm standby redundancy strategies and seems like more researches are needed with respect to redundancy strategy.

In the 1970s, Gopal et al. (1978) (GAG), and Nakagawa and Nakashima (1977) (NAN) introduced iterative heuristics for redundancy allocation. In the 1980s, the methods were improved by Kohda and Inoue (1982) (KI), and Shi (1987) (SHI). Kim and Yum (1993) (KY), and Jianping (1996) (JP), concentrated on improving solutions from a local optimum. Other heuristics include the work by Dinghua (1987), Nakagawa and Miyazaki (1981). Meta-heuristic approaches for single objective problems before year 2000 include GA (Coit & Smith, 1996), penalty guided GA (Coit & Smith, 1996), hybrid NN-GA (Coit & Smith, 1996), SA (Ravi et al., 1997), Ant system (Liang & Smith, 1999), etc.

Table 1 (a)
Exact and Mathematical programming approaches for RAP (Single Objective Problems)

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Prasad et al. (2001)	Series- parallel	Deterministic	Active	Percentile life	Lexicographic search	An upper bound is used to reduce the search space
Ng & Sancho (2001)	Series- parallel/ overspeed protection system	Deterministic	Active	System reliability	Hybrid DP/depth first search	
Yalaoui et al. (2005)	Series- parallel	Deterministic	Active	System cost	DP	
Onishi et al. (2007)	Series- parallel	Deterministic	Active	System reliability	Improved surrogate constraint	
Djerdjour and Rekab (2001)	Series- parallel	Deterministic	Active	System cost	Branch and bound	A heuristic for finding a good lower bound is presented along with some implicit enumeration criteria
Ramirez-Marquez et al. (2004)	Series- parallel	Deterministic	Active	Max-Min reliability	Mixed integer linear programming	
Lee et al. (2003)	Series- parallel	Deterministic	Active	Max-Min reliability	Comparison of Min-Max approach and NN	
Hsieh (2003)	Series- parallel	Deterministic	Active	System reliability	Simple linear approximation	Multiple component choices, Constraints must be linear and separable
Hsieh (2002)	Series- parallel	Deterministic	Active	System reliability	Two-Phase Linear Programming	The method provides a good lower bound for branch-and-bound algorithm or artificial methods
Billionnet (2008)	Series- parallel	Deterministic	Active	System reliability	Integer linear programming	
Nourelfath & Nahas (2003)	Series	Deterministic	-	System reliability	Quantized hopfield networks	For each component, there are different technologies available
Amari (2010)	*k*-out-of-*n*	deterministic	Active/warm standby	System reliability	linear programming (LP)-based branch-and-bound	Arbitrary general Distributions (such as Weibull or Gamma)
Tannous et al. (2011)	Series-parallel	deterministic	Warm standby	System reliability	GA and exact integer programming for reformulated model	SBDD for driving the objective function , exponential failure distribution

Table 1 (b)
Exact and Mathematical programming approaches for RAP (Multi Objective Problems)

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Mahapatra (2009)	Series- parallel	Deterministic	Active	System reliability and Entropy	Global criterion method	Non-linear cost constraint
Khalili-Damghani & Amiri(2012)	Series-parallel	Deterministic	Active	System reliability and cost	Epsilon constraint along with DEA (to prune the pareto set)	
Sadjadi et al. (2014)	Series-parallel	Deterministic	Active and cold standby	System reliability, cost and weigh	Compromise programming	Switch reliability is imperfect, Earlang time to failure distribution
Soltani et al. (2015)	Series-parallel	Deterministic	Active and cold standby	System reliability, cost and entropy/weight entropy	Compromise programming	Switch reliability is imperfect, Earlang time to failure distribution
Cao et al. (2013)	Series-parallel	Deterministic	Active	System reliability, cost and weight	Decomposition approach	
Khalili-Damghani et al. (2013)	Series-parallel	Deterministic	Active	System reliability, cost and weight	A decision support system based on TOPSIS, modified ε-constraint and DEA	

Table 2 lists the related works in the literature after year 2000. Active and cold standby redundancy strategies have been studied more and more researches are needed regarding the warm standby redundancy.

Table 2 (a)
Heuristic and Meta-heuristic approaches for RAP (Single Objective Problems)

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Ha (2004)	Bridge, Series-parallel	Deterministic	Active	System reliability	Multi-path heuristics called tree and scanning	There are no other restrictions such as separable, linear, and convex.
You & Chen (2005)	Series-parallel	Deterministic	Active	System reliability	Heuristic (based on greedy method and GA)	Assumption of Fyffe (1968) hold.
Sadjadi & Soltani (2009)	Series-parallel	Deterministic	Active	System reliability	Heuristic and GA	Allowing one component type
Coit & Liu (2000)	k-out-of-n	Deterministic	Active	System reliability	Standard algorithm for zero-one IP	Exponential time to failure, allowing one component type
Kulturel-Konak et al. (2003)	k-out-of-n	Deterministic	Active	System reliability	TS	Exponential time to failure, allowing one component type
Ryoo (2005)	Complex systems	Deterministic	Active	System reliability	Robust meta-heuristics (TS)	
Kim et al. (2004)	Series-parallel	Deterministic	Active	System reliability	SA	
Ravi (2004)	Complex/series-parallel	Deterministic	Active	System reliability	GDA	
Rocco (2000)	Complex	Deterministic	Active	System reliability	CEA	
Sadjadi & Soltani (2012)	Series-parallel	Deterministic	Active	System reliability	Heuristic and HBMO	Mix of components
Hsieh & Yeh (2012)	Series-parallel	Deterministic	Active	System reliability	Penalty guided bees search	Mix of components
Liang & Smith (2004)	k-out-of-n	Deterministic	Active	System reliability	ACO	
Nahas & Nourelfath (2005)	Series	Deterministic	Active	System reliability	Ant system with local search	One technology can be used for each component
Ahmadizar & Soltanpanah (2011)	series	Deterministic	Active	System reliability	ACO	One technology can be used for each component
Nahas et al. (2007)	k-out-of-n	Deterministic	Active	System reliability	Coupling ACO and DC	
Beji et al. (2010)	Series-parallel	Deterministic	Active	System reliability	Hybrid PSO with local search	An adaptive penalty function was proposed.
Chen & You (2005)	Series-parallel	Deterministic	Active	System reliability	IA	Multiple component choices
Nahas & Thien-My (2010)	Series-parallel	Deterministic	Active	System reliability	HS	
Liang & Wu (2005)	Series-parallel	Deterministic	Active	System reliability	VND	
Liang & Chen (2007)	Series-parallel	Deterministic	Active	System reliability	VNS	
Coit (2001)	Series-parallel	Deterministic	Cold standby	System reliability	Integer programming	Multiple component choices for each subsystem and imperfect switching
Coit (2003)	Series-parallel	Deterministic	Active and Cold standby	System reliability	Integer programming	Assumption of Coit (2001) hold.
Tavakkoli-Moghaddam et al. (2008)	Series-parallel	Deterministic	Active and Cold standby	System reliability	GA	Assumptions of Coit (2003) hold.
Tavakkoli-Moghaddam & Safari (2007)	Series-parallel	Deterministic	Active and cold standby	System reliability	-	Mixing components is allowed.
Safari & Tavakkoli-Moghaddam (2010)	Series-parallel	Deterministic	Active and cold standby	System reliability	Memetic algorithm	No component mixing is allowed.
Karimi et al, (2011)	Series-parallel	Deterministic	Cold standby	System reliability	GA and SA	Exponential and hypo-exponential time to failure distribution
Chambari et al. (2013)	Series-parallel	Deterministic	Active and cold standby	System reliability	SA	Assumptions of Coit (2003) hold.
Safaei et al. (2012)	Series-parallel	Deterministic	Active	System reliability	Annealing-based PSO	Assumptions of Hsieh (2002) hold.
Najafi et al. (2013)	Series-parallel	Deterministic	Active	Mean time to failure	Tuned SA and GA	Mixing components is not allowed
Yeh (2014)	Series-parallel	Deterministic	Active	System reliability	OSSO	Mixing components is allowed.
Soltani et al. (2013)	Series-parallel	Deterministic	Active	System reliability	Heuristic and HBMO	Mixing components is allowed. Price discounting are considered.

Table 2 (b)
Heuristic and Meta-heuristic approaches for RAP (Multi Objective Problems)

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Salazar et al. (2006)	Complex, series-parallel, life-support system in a space capsule	Deterministic	Active	System reliability and cost	NSGA-II	Three types of problems including reliability allocation, RAP and RRAP are considered.
Coit & Konak (2006)	Series-parallel	Deterministic	Active	Subsystem reliability	Multiple weighted objective heuristic	
Zhao et al. (2007)	Series-parallel, Series-parallel with k-out-of-n:G subsystem (gearbox reliability optimization)	Deterministic	Active	Subsystem cost and weight	multi-objective ant colony system	
Taboada et al. (2007)	Series-parallel	Deterministic	Active	System reliability, cost and weight	NSGA-II	Pareto set is pruned through data clustering (k-means)
Taboada & Coit (2008)	Series-parallel	Deterministic	Active	System reliability, cost and weight	Multiple objective GA (MOEA-DAP)	
Kulturel-Konak et al. (2008)	Series-parallel	Deterministic/stochastic reliability	Active	System reliability, cost and weight/risk	Multinomial TS with MC to Prune Pareto optimal set)	Multiple prioritized objectives were considered.
Liang & Lo (2010)	Series-parallel	Deterministic	Active	System reliability and cost/weight	MOVNS	Problem of Fyffe et al. (1968) and Salazar et al. (2006) were considered.
Suman (2003)	Series-parallel , life support system in a capsule	Deterministic	Active	System reliability, cost and weight	SMOSA, UMOSA, PSA, PDMOSA and WMOSA	
EbrahimNezhad et al. (2011)	Series-parallel	Deterministic	Active and Cold Standby	System reliability and profit	NSGA-II	Erlang time to failure
Safari (2012)	Series-parallel	Deterministic	Active and Cold Standby	System reliability and cost	NSGA-II	Erlang time to failure
Chambari et al. (2012)	Series-parallel	Deterministic	Active and Cold Standby	System reliability and cost	NSGA-II	Erlang time to failure
EbrahimNezhad et al. (2012)	Series-parallel	Deterministic	Active and Cold Standby	System reliability and profit	NSGA-II and Memetic algorithm	Erlang time to failure
Khalili-Damghani et al. (2013)	Series-parallel	Deterministic	Active	System reliability, cost and weight	DSAMOPSO, AUGMECON, NSGA-II, CTV-MOPSO	
Zhang et al. (2014)	Series-parallel	Deterministic	Active	System reliability, cost and weight	BBMOPSO followed by k-Means and Hierarchical clustering	Equivalent components
Azizmohammadi et al. (2013)	Series-parallel	Deterministic	Active and standby	System reliability (max-min), cost and volume	HMOICA (hybrid ICA and GA)	
Shelokar et al. (2002)	Series-parallel, complex, bridge	Deterministic	Active	System reliability and cost	Ant algorithm	

2.1.2 Non-deterministic models

Non-deterministic models assume that at least one of the design parameters is not known, precisely. Regarding the level of access to the historical data the uncertainty can be considered in the following forms.

2.1.2.1 Stochastic Uncertainty

In the stochastic uncertainty either the distribution of the data is specified or mean and standard deviation of the data are known. One way to formulate these problems is to maximize the expected value of system reliability (e.g. Rubinstein et al., 1997). However, this method is not suitable for designers who are risk-averse. Therefore, both expected value and variance of the system reliability (e.g. Marseguerra et al., 2005) or a function of both such as coefficient of variation (e.g. Tekiner & Coit, 2011) is taken into consideration. In case where both expected value and variance of the system reliability are considered the problem is treated as a multi-objective problem. Table 3 lists the RAP with respect to stochastic uncertainty.

Table 3
Stochastic uncertainty

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Coit & Smith (2002)	Series-parallel	Random scale parameter for weibull distribution	Active	Lower percentile of system time to failure	GA	The scale parameter doesn't change with time
Coit & Wattanapongsakorn (2004)	Series-parallel, bridge, fault tolerant distributed system	Stochastic component reliability	Active	System reliability and variance	Stochastic optimization	Risk is considered in decision making (risk-averse)
Yeh (2003)	Series-parallel, Network	Stochastic component reliability	Active	System cost	MCS-RSM	MCS is used to find the estimated reliability then BBD of RSM is used to find the reliability function
Marseguerra et al. (2005)	Network	Stochastic component reliability	Active	Expected and variance of system reliability	GA and MC	Multiple choices of component types
Tekiner & Coit (2011)	Series-parallel	Stochastic component reliability	Active	Coefficient of variation	Neighborhood search, and linear integer programming	With and without component mixing
Rubinstein et al. (1997)	Series-parallel	Stochastic component reliability	Active	Expected values of system reliability	Simulation and GA	Cost is a separable nonlinear function
Reddy et al. (2011)	Network	Stochastic component reliability	Active	System reliability	Simulation method	Identical components
Zhao & Liu (2003)	Series-parallel , complex(bridge),communication network, lifetime-support system, series	Random lifetime, stochastic cost	Active/ standby	Mean system-lifetime,α -system lifetime, or system reliability	Stochastic programming technique solved by stochastic simulation, NN and GA	There is only one type of elements available, switch reliability is perfect
Yadavalli et al. (2007)	Series-parallel	Resource Chance constraint	Active	System reliability	Branch and bound	Uniform, normal, log-normal distributions
Li & Hu (2008)	Series-parallel	Random lifetimes	Active/ standby	Survival function	Stochastic comparison	
Zafiropoulos & Dialynas (2004)	Power electronic device	Component failure rate uncertainty	-	System structure considering System reliability and cost	SA	Triangular and normal distributions. The failure rates are simulated using LHS method

2.1.2.2 Interval Uncertainty

In the interval uncertainty it is assumed that just the information about the lower and upper bounds of the interval is known. Yokota et al. (1995) are the first who formulated the optimal design problem of system reliability as a nonlinear integer programming problem with interval coefficients. They transformed the problem into a bi-criteria 0-1 nonlinear programming problem without interval coefficients, and solve it directly through GA. In general, there are some ways to formulate interval reliability problems, which are maximization of the left bound and/or center of the interval (Yokota et al., 1996; Taguchi et al., 1998), nonlinear goal programming formulation (Taguchi et al., 1997), etc. There are some methods to deal with such problems such as GA (Taguchi & Gen, 1997; Yokota et al., 1996), hybrid GA and SA (Taguchi et al., 1998), Improved GA (Taguchi & Yokota, 1999), etc. Table 4 lists the related works after year 2000.

Table 4(a)
Redundancy allocation under interval uncertainty (Single objective Problems)

Reference	System configuration	Uncertainty state	Stretegy	System performance	Solution method	Other considerations
Gupta et al. (2009)	Series-parallel	Interval component reliability	Active	System reliability	Advanced GA with interval fitness function	Interval valued mission time, identical components
Bhunia et al. (2010)	Series-parallel	Interval reliability and stochastic cost	Active	System reliability	Real-coded GA	Resource constraints are chance constraints
Sahoo et al. (2010)	Hierarchical series-parallel, parallel-series, complex, k-out-of-n	Interval reliability	Active	System reliability	GA	
Taguchi & Yokota (2011)	Series-parallel	Interval reliability	Active	System reliability	Hybrid GA, SA and FLC	
Sahoo et al. (2013)	Bridge	Interval reliability, cost and amount of resources	Active	System reliability	GA	Low level (component) redundancy and high level (system) redundancy are considered.

Table 4(b)
Redundancy allocation under interval uncertainty (Multi-objective Problems)

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method	Other considerations
Sahoo et al. (2012)	Series-parallel	Interval reliability and cost	Active	System reliability and cost	GA,Tchebycheff, weighted Tchebycheff and lexicographic weighted Tchebycheff	Identical components
Bhunia & Sahoo (2012)	Series-parallel	Interval reliability and cost	Active	System reliability and cost	GA, Global criterion method, Tchebycheff and weighted Tchebycheff	Identical components
Roy et al. (2014)	Series-parallel (break lining manufacturing plant)	Interval component reliability and cost and system entropy	Active	System reliability and cost with entropy constraint	Entropy based region reducing GA	System cost depends on reliability of the components

2.1.2.3 Fuzzy Uncertainty

The concept of fuzzy reliability has been introduced and formulated in the book by Cai (1996). One form of fuzzy uncertainty is having flexible goals and constraints (e.g. Park, 1987). Another form is having imprecise data for components reliabilities/lifetimes, cost, weight, etc. Cheng and Mon (1993) used the α-cut of a triangular fuzzy number to get the interval and find the fuzzy reliability of the series system and the parallel system.

Table 5
Fuzzy uncertainty

Reference	System configuration	Uncertainty state	Strategy	System performance	Solution method	Other considerations
Ravi et al. (2000)	Series-parallel	Fuzzy goals and constraints	Active	System reliability, cost, weight and volume	A global optimization meta-heuristics (Threshold accepting)	Linear membership functions have been assumed for all the goals/objectives.
Zhao & Liu (2005)	Series-parallel	Fuzzy lifetimes	Standby	Expected system lifetime, α-system lifetime, system reliability (EVM, CCP, DCP)	Integrated fuzzy simulation, NN and GA	
Hou & Wu (2006)	Series-parallel	Fuzzy reliability	Active	System reliability	Fuzzy simulation-based GA	Nonlinear chance constrained programing models and three goal programing models based on possibility and credibility measures
Mahapatra & ROY (2011)	Series-parallel	Fuzzy reliability, cost and weight	Active	System reliability	Fuzzy parametric geometric programming	
Yao et al. (2008)	Series, parallel	Triangular fuzzy numbers	Active	System reliability	signed distance method to defuzzify	
Lee et al. (2012)	Parallel	Level (λ,ρ) interval-valued fuzzy numbers	Active	System reliability	signed distance method to defuzzify	
Han et al. (2006)	Flexible Manufacturing Cells	Triangular fuzzy numbers	-	System reliability	Fuzzy fault tree	
Jameel & Radhi (2014)	Series-parallel	Fuzzy reliability and flexible constraints	Active	System reliability	Penalty function mixed with Nelder and Mend's algorithm	
			Multi-Objective			
Sasaki & Gen (2003)	Series-parallel	Fuzzy objectives	Active	System reliability and cost	Hybrid GA	With Generalized upper bounding (GUB) structure
Chen & Liu(2011)	Series-parallel	Type-2 fuzzy lifetime	Standby	System lifetime and cost	Fuzzy Goal programming and Approximation approach based PSO	Switching device of the standby system is perfect

Chen (1994) used fuzzy numbers to find the fuzzy reliability of both the series system and the parallel system. Mon and Cheng (1994) used the α -cut of fuzzy number to derive a non-linear program of the fuzzy system in both the series and parallel cases. Singer (1990) considered the fuzzy reliability of both series and parallel systems using an approximation of a fuzzy binary operation ⊗ with two L-R type fuzzy numbers. Chen (1996) presented a method for fuzzy system reliability analysis based on fuzzy time series and the α-cuts operations of fuzzy numbers. Hong et al. (1997) analyzed fuzzy system reliability by the use of *t*-norm based convolution of fuzzy arithmetic operation, where the reliability of each component is represented by L-R type fuzzy numbers. Table 5 lists other works after year 2000.

2.1.2.4 Intuitionistic fuzzy and vague sets

Kumar et al. (2011) extended the concept of fuzzy set by idea of triangular intuitionistic fuzzy sets (IFS) and proposed a general procedure to construct the membership function and non-membership function of the reliability function using intuitionistic fuzzy failure rate. The major advantage of using intuitionistic fuzzy sets over fuzzy sets is that intuitionistic fuzzy sets separate the positive and the negative evidence for the membership of an element in a set (Mahapatra & Roy, 2009).Table 6 lists the works related to intuitionistic fuzzy and vague sets.

Table 6
Intuitionistic fuzzy and vague sets

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method	Other considerations
Kumar et al. (2006)	Series, parallel, Marine power plant	Interval valued trapezoidal vague sets	Active	System reliability	A method for analyzing the fuzzy system reliability	An interval is considered for the grade of membership and non- membership of an element (interval valued vague set)
Chen (2003)	Series, parallel, series-parallel	Triangular vague set for components reliabilities	Active	System reliability	A method based on the vague set theory	A real number in [0, 1] is considered for the grade of membership and non-membership of an element
Kumar et al. (2007)	Series, parallel	LR type interval valued triangular vague set for component reliability	Active	System reliability	Tw (the weakest t norm) based arithmetic operation	The results are exact
Kumar & Yadav (2012)	Series, parallel	Intuitionistic fuzzy failure rate	Active	System reliability	Non-linear programming techniques	Different types of intuitionistic fuzzy failure rate are considered.
Mahapatra & Roy (2009)	Series, parallel, electric network model of dark room	Triangular intuitionistic fuzzy reliability	Active	System reliability	(α, β)-cut	
Pandey et al. (2011)	Series, parallel, web server	Triangular intuitionistic fuzzy reliability	Active	System reliability	A method based on IFS theory	
Mahapatra & Roy (2014)	Complex system	Intuitionistic fuzzy cost	Active	System reliability	Intuitionistic fuzzy optimization method	

2.1.2.5. Fuzzy-random Uncertainty

Due to subjective judgment, imprecise human knowledge and perception in capturing statistical data, the real data of lifetimes in many systems are both random and fuzzy in nature. Table 7 lists the related work to fuzzy-random uncertainty.

Table 7
Fuzzy-random uncertainty

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method	Other considerations
Zhao & Liu (2004)	Multistage systems and communication network systems	Random-fuzzy lifetimes	Standby	Expected system lifetime, (α,β)-system lifetime and system reliability	Integrated random fuzzy simulation, NN and GA	
Wang & Watada (2009)	Parallel-series	Random-fuzzy lifetimes	Active	System reliability	Hybrid binary PSO	
Wang & Watada (2009)	Parallel-series	Random-fuzzy lifetimes	Active	System reliability/cost (Mean chance measure)	Fuzzy random simulation and GA	Compute the reliability with convex and non-convex lifetimes
Wang et al. (2012)	Series-parallel (some subsystems with gradual failure (e.g. single helical gear reducer) and some with sudden failure)	Random-fuzzy lifetime	Active	System reliability	Saddlepoint Approximation (SAP)- simulation for gradual failure and statistics-based reliability analysis for components with sudden failure	There is a time-dependent degradation process
Nematian et al. (2008)	Series-parallel	Random-fuzzy lifetimes	Active /Standby	Expected value of system lifetime	Integer programming	

2.1.2.6 Robust optimization

Robust approaches are based on the idea that the resulted robust solution would be immune against different realizations of uncertain parameters. There are two main robustness measures: one based on regret (e.g. Feizollahi & Modarres, 2012; Soltani et al., 2013) and the other one based on the realized performance (Feizollahi et al., 2014; Soltani & Sadjadi, 2014). Table 8 lists the existing works in the literature. Amongst the works, just one work, i.e. the work by Soltani et al. (2013) considers cold standby strategy and more researches are needed with respect to redundancy strategy. The author has currently an under review work considering the redundancy strategy choices. Developing other robust optimization techniques is of interest and the author is currently working on this subject matter.

Table 8
Robust RAP

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method
Feizollahi & Modarres (2012)	Series- parallel	Interval uncertainty	Active	Min-Max regret of System reliability	MIP and Benders decomposition
Soltani et al. (2013)	Series- parallel	Interval uncertainty	Cold standby	Min-Max regret of System reliability	Benders decomposition, GA and Enumeration method
Soltani & Sadjadi (2014)	Series- parallel	Fuzzy uncertainty	Active	Expected value and variance of the system reliability	Branch and cut
Feizollahi et al. (2014)	Series- parallel	Budgeted uncertainty	Active	System reliability	MIP and Benders decomposition

2.1.2.7 Chaos uncertainty

Chaos means the oscillations, which seem random but in fact they are generated by the deterministic nonlinear model. The idea of chaos theory application in the reliability modeling appears in Zou and Li (2001). The integration of fuzzy reliability model with the phase portraits of variables creates preconditions for the construction of phase portrait reflecting the system reliability dynamics (Rotshtein et al., 2012). To the best of our knowledge, in the area of RAP just one work for chaos uncertainty has been reported as presented in Table 9 and more researches in this area would be interesting.

Table 9
Chaos uncertainty for RAP

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method	Other considerations
Rotshtein et al. (2012)	Series-parallel	Deterministic	Active	System reliability	GA	Integration of fuzzy logic and chaos theory

2.2 Multi-level redundancy (Modular redundancy)

As mentioned earlier, redundancy at the component level is more effective than redundancy at the system level. This is true under some specific assumptions but Boland and EL-Neweihi (1995) showed that this was not true in the case of redundancy with non-identical spare parts. Modular redundancy can be more effective than component redundancy. In other words, providing redundancy at high levels such as modules or subsystems can be more economical than providing redundancy at low level of components. Multi-level redundancy allocation problems (MRAP) have been addressed, considering the redundancy at the subsystem level (modular redundancy). Another form of this problem is multiple multi-level redundancy allocation problem (MMRAP) in which all available items for redundancy (system, module and component) can be simultaneously chosen. During the optimization process, the values of design variables expressing redundancy are interdependent, since they are hierarchical, i.e., the reliability of an upper level unit depends on the reliability of its lower level units. In the hierarchical structure of a reliability system, the system level is the top most level and the component level is the lowest. Subsystem or module levels are located between the top level and the bottom level. Table 10 lists the related works to multi-level or modular redundancy. To the best of our knowledge, just one work, i.e. the work by Pourdarvish and Ramezani (2013), considers cold standby redundancy. Therefore, more researches on redundancy strategy are needed. More researches are also required in the area of multi-objective multi-level redundancy. Non-deterministic multi-level redundancy is an interesting area too.

Table 10
Multi-level redundancy

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method	Other considerations
Yun & Kim (2004)	Multi-level series	Deterministic	Active	System reliability	Heuristic and GA	Only one unit can be used in a direct line
Yun et al. (2007)	Multiple multi-level series (hierarchical structure)	Deterministic	Active	System reliability	Simple GA (SGA)	If an item is used, all its sibling items should be used or its function should be satisfied by the corresponding child items.
Jang & Kim (2011)	Multiple multi-level	Deterministic	Active	System reliability	TS	TS of memory-based mechanisms that balances intensification with diversification via the short-term and long-term memory
Kumar et al. (2009a)	Multilevel series and series–parallel	Deterministic	Active	System reliability	Hierarchical GA	
Yeh (2009)	Multiple multi-level	Deterministic	Active	System reliability	Two stage discrete PSO (2DPSO)	Assumptions of Yun et al. (2007) hold.
Wang et al. (2010a)	Multilevel redundancy	Deterministic	Active	System reliability	Memetic algorithm with breadth-first crossover and breadth-first mutation	
Wang et al. (2010b)	Multilevel redundancy	Deterministic	Active	System reliability	PSO	
He et al (2013)	Multilevel redundancy	Deterministic	Active	System reliability	Hybrid GA based on the two dimensional redundancy encoding mechanism	
Pourdarvish & Ramezani (2013)	Multilevel redundancy	Deterministic	Cold standby	System reliability	MA and Hierarchical GA	
			Multi-objective Problems			
Kumar et al. (2009 b)	Multilevel redundancy	Deterministic	Active	System reliability and cost	MOHGA including SPEA2 and NSGA-II	

2. Reliability Allocation

The reliability allocation problems assume fix or known redundancy levels and they aim at determining the reliability levels. There are some methods for determining reliability levels such as Hooke and Jeeves (H-J) pattern search (Tillman et al., 1977), GAG2 (Gopal et al., 1980), to name a few. For more study on these methods, the readers can view the work by Tillman (1985). Table 11 lists the reliability allocation models existed in the literature.

Table 11(a)
Reliability allocation (Single Objective Problems)

Reference	System configuration	Uncertainty state	System performance	Solution method	Other considerations
Park (1987))	Two-component series	Deterministic	System reliability	Fuzzy non-linear programming	
Ravi et al. (2000)	Complex	Fuzzy goals and constraints	System cost	A global optimization meta-heuristics (Threshold accepting)	
Mahapatra & Mahapatra (2010)	Series	Fuzzy reliability and cost	System reliability/ System cost	Fuzzy parametric geometric programming	Objective and constraint are posynomial functions
Mahapatra & Roy (2012)	Bridge system	Triangular fuzzy number for reliability	System reliability	α -cut	
Elegbede et al. (2003)	Series-parallel	Deterministic	System cost	ECAY (exact)	
Yalaoui et al. (2005)	Parallel-series	Deterministic	System cost	Resolution method	Different technologies which have the same function are used in parallel, convex cost functions
Sriramdas et al. (2014)	Series (transceiver)	Trapezoidal fuzzy numbers	System reliability	Approximation method based on linear programming for trapezoidal fuzzy numbers	Centroid method of defuzzification is used to evaluate weighting factor

Table 11(b)
Reliability allocation (Multi Objective Problems)

Reference	System configuration	Uncertainty state	System performance	Solution method	Other considerations
Sakawa & Yano (1985)	Series (standby)	L-R type fuzzy numbers for DM's judgment	System reliability, Cost, weight, volume and the product of weight and volume	Fuzzy sequential proxy optimization technique (FSPOT)	Reliability of switch is one, the state of components are independent of each other
Huang et al. (2005)	Series-parallel	Deterministic	System reliability, Cost and weight	IIMOM and ANN	
Mahapatra & Roy (2006)	Series, complex	Generalized fuzzy set	System reliability, Cost	Fuzzy multi-objective mathematical programming	
Mahapatra & Roy (2006)	Series	Crisp/fuzzy cost and flexible constraints	System reliability/ Cost	Fuzzy parametric geometric programming	
Mahapatra et al. (2010)	LCD display system	Deterministic	System reliability and Cost	Intuitionistic fuzzy programming	

As observed, the problem of reliability allocation has gained less attention amongst researchers in comparison with RAP or RRAP. The uncertainty type considered in the literature for this kind of problem is of fuzzy uncertainty. Considering other forms of uncertainty can be an interesting research area.

3. Reliability- Redundancy Allocation

The reliability-redundancy problem was initially introduced by Misra and Ljubojevic (1973). They treated the number of redundancies as real variables and solved the problem as a reliability allocation problem by using Lagrange multipliers. **A** trial and error approach was used afterward to obtain the integer solution for the number of redundancies. The problem has been studied on four typical system configurations such as series, series-parallel, complex and over-speed protection system for a gas turbine. The aim is to determine reliability levels and redundancy levels to maximize system reliability subject to constraints on cost, weight and volume usually in nonlinear forms. The techniques for solving RRAP mainly combine the methods for reliability allocation and the methods for redundancy allocation. Tillman et al. (1977) were among the first to solve RRAP using *THK* method, which is based on a combination of Hooke-Jeeves (H-J) pattern search (Hooke & Jeeves, 1961) for reliability allocation and the Aggrawal-Gupta-Misra (A-G-M) greedy heuristic (Aggrawal et al., 1975) for redundancy allocation in a series-parallel system. Other combinations include H-J&GAG (Gopal et al., 1978), H-J&S-V (Sharama & Venkateswaran, 1971), H-J&N-N (Nakagawa & Nakashima, 1977), H-J&K-I (Kohda & Inoue, 1982), GAG2 (Gopal et al., 1980) and *GAG, GAG2&S-V, GAG2&NN, GAG2&K-I*, where the first heuristic finds reliability levels and the second heuristic finds redundancy levels. Besides, Xu et al. (1990) proposed XKL method, which uses a heuristic to find redundancy levels and an analytical approach to find reliability levels. Jacobson and Arora (1996) proposed a Simplex search for solving RRAP. Mathematical programming methods include *LMBB* method (Kuo et al., 1987) which combines the branch-and-bound and Lagrange multipliers methods, and surrogate constraint (Hikita et al., 1992). Meta-heuristic approaches include GA (Yokota et al., 1996; Hsieh et al., 1998) and the evolutionary algorithm developed by Prasad and Kuo (1997). After year 2000 with the advent of the new heuristic and meta-heuristics, methods such as Column Generation, IA, SA, PSO, HS, ICA, cuckoo search separately or in hybrid forms have been implemented to this problem. Regarding the method for multi-objective reliability-redundancy problems before year 2000 we can refer to goal programming and goal attainment formulations (e.g. Dhingra, 1992; Rao & Dhingra, 1992). Table 12 summarizes the existing work after year 2000. Note that the table is sorted based on the solution method. To the best of our knowledge, amongst the paper investigated, just two works have studied cold standby strategy (Ardakan & Hamadani, 2014; Liu, 2006) and a few works are in non-deterministic area. Considering other redundancy strategies and other forms of uncertainties can be a fruitful area of research.

Table 12(a)

Reliability- Redundancy Allocation (Single Objective Problems)

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method
Sun et al. (2001)	Bridge, network	Deterministic	Active	System reliability/cost	Convexification method (exact)
Lee et al. (2002a), (2002b)		Deterministic	Active	System reliability	Hybrid NN-GA with FLC
Ha & Kuo (2005)	Series, bridge	Deterministic	Active	System reliability	Scaling method based on multi-path iterative heuristic
Liu (2006)	Series-parallel, k-out-of-n:G	Deterministic	Active/standby	System reliability/cost	A combination method including Hooke–Jeeves pattern search and dynamic programming, applying dominating sequences
Kim et al. (2006)	Series, series-parallel, complex (bridge)	Deterministic	Active	System reliability	SA
Mori et al. (2007)	Series-parallel	Deterministic	Active	System reliability	Hybrid SA-GA
Chen (2006)	Series, series-parallel, complex and over-speed protection system	Deterministic	Active	System reliability	IA
Hsieh & You (2011)	Series, series-parallel, complex and over-speed protection system	Deterministic	Active	System reliability	IA based two-phase
Coelho (2009)	Over-speed protection system for a gas turbine	Deterministic	Active	System reliability	DE based on chaotic sequences using Lozi's map
Coelho et al. (2009)	Over-speed protection system for a gas turbine	Deterministic	Active	System reliability	HS with DE
Zou et al. (2010)	Complex (bridge), Over-speed protection system for a gas turbine, large scale system	Deterministic	Active	System reliability	NGHS
Zou et al. (2011)	Complex (bridge), Over-speed protection system for a gas turbine	Deterministic	Active	System reliability	EGHS (hybrid HS-PSO)
Wang & Li (2012)	Series, series-parallel, complex and over-speed protection system	Deterministic	Active	System reliability	DE and HS
Yeh & Hsieh(2011)	Series, series-parallel, complex and over-speed protection system	Deterministic	Active	System reliability	ABC
Garg et al. (2013)	Series, series-parallel, complex, over-speed protection system, Life support system in a space capsule	Deterministic	Active	System reliability/system cost	Two phase algorithm including ABC
Afonso et al. (2013)	Series, series-parallel, complex and over-speed protection system	Deterministic	Active	System reliability	Modified ICA
Coelho (2009b)	Series, series-parallel and over-speed protection system	Deterministic	Active	System reliability	SOMA with a Gaussian operator
Zia & Coit (2010)	Series-parallel	Deterministic	Active	System reliability	Column Generation
Coelho (2009)	Complex (bridge), over-speed protection system	Deterministic	Active	System reliability	PSO-GC
Wu et al. (2011)	Series, series-parallel, complex, over-speed protection system, large scale system	Deterministic	Active	System reliability	Improved PSO (IPSO)
Garg & Sharma (2013)	Pharmaceutical Plant	Deterministic	Active	System reliability	PSO
Tan et al. (2013)	series, series-parallel, complex (bridge), Over-speed protection	Deterministic	Active	System reliability	DE-PSO with chaotic local search
Zhang et al. (2013)	series, series-parallel, complex (bridge), Over-speed protection, large scale	Deterministic	Active	System reliability	Hybrid HS/ LXPM –IPSO with Golden search (GS)
Valian & Valian (2013)	series, series-parallel, complex (bridge), Over-speed protection, large scale system	Deterministic	Active	System reliability	Cuckoo search by Lévy flights
Valian et al. (2013)	series, series-parallel, complex (bridge), Over-speed protection, large scale system	Deterministic	Active	System reliability	Improved cuckoo search
Kanagaraj et al. (2013)	series, series-parallel, complex (bridge), Over-speed protection	Deterministic	Active	System reliability	Hybrid cuckoo search-GA
Ardakan & Hamadani (2014)	series, series-parallel, complex (bridge)	Deterministic	Cold standby	System reliability	Modified GA
Mahato et al. (2012)	Complex bridge system, over speed protection system for a gas turbine	Interval reliability	Active	System reliability	GA

Table 12(b)
Reliability- Redundancy Allocation (Multi Objective Problems)

Reference	System configuration	Uncertainty state	Redundancy strategy	System performance	Solution method
Huang (2004)	Over-speed protection system for a gas turbine	Deterministic	Active	Reliability, cost and weight	Interactive physical programming
Ebrahimipour & Sheikhalishahi (2012)	Series-bridge	Triangular fuzzy reliability	Active	System reliability and cost considering price discounting	MOPSO
Sheikhalishahi et al. (2013)	series, series–parallel, and complex (bridge)	Deterministic	Active	System reliability, cost, weight and volume	hybrid GA-PSO
Mutingi & Mapfaira (2013)	Series	Fuzzy goals and constraints	Active	System reliability and cost	Fuzzy multi-objective GA
Garg & Sharma (2013)	Series–parallel (pharmaceutical plant)	Intuitionistic fuzzy reliability and flexible constraints	Active	System reliability and cost	MOPSO
Garg et al. (2014)	Series-parallel, Complex Bridge, Over-speed protection	Triangular fuzzy reliability	Active	System reliability and cost	PSO
Garg et al. (2014)	Series-parallel, Complex	Intuitionistic fuzzy reliability	Active	System reliability and cost	Intuitionistic fuzzy programming technique and PSO

4. Concluding remarks

In the present research, three types of reliability optimization methods including redundancy allocation, reliability allocation and reliability-redundancy allocation have been investigated from different perspectives, which have been collected in a table format. Since the area of the reliability optimization problems is vast and so many works have been carried out in this area, the focus of this study has been on binary state non-repairable systems and the problems have been categorized with respect to different criteria. Scholars and researchers who wish to study on each of the mentioned area, need to flashback to the initial works and see the changing trend of the subjects from the scratch so that they can perceive the need for developing new models and methods in reliability. For this purpose, for each area the author has tried to have a quick review on early works and for each classification some of the prominent works in the literature have been introduced so that the interested readers can refer them and find other related papers to study in depth. This study has classified the literature in a novel way and at the end of each classification research guides for further researches have been proposed to help researchers and seems like the same is needed for multistate and/or repairable systems.

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